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Research Paper

Discrete element modelling of top soil burial using a full scale mouldboard plough under field conditions

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In order to improve the grain crop yield of non-wetting sandy soils, mouldboard ploughs are again being used in Australia. To improve the effectiveness of top soil burial from ploughing the most suitable operating parameters need to be determined. The discrete element method (DEM) has the potential to model soil–mouldboard plough interactions relating to both soil movement and tillage forces. A full scale mouldboard plough was tested in the field and then simulated using DEM. The draught forces predicted by DEM were of similar magnitude to those calculated using ASABE's Agricultural Machinery Management Data (D497.7 R2015). The DEM model predicted top soil burial to a similar depth in the soil profile as was measured in the field. However, DEM predictions of lateral and forward soil movements of the buried top soil were greater than that measured in the field. The DEM predictions showed that increasing speed from 5 to 15 km h^{-1} gave a 40% increase in draught and a significant reduction in the depth of top soil burial. Increasing the tillage depth from 200 to 350 mm gave a 270% increase in draught but very little change in depth of burial of the top soil. The use of a skimmer was predicted to increase the draught by 4% and increase the amount of top soil buried below 100 mm depth.

1. Introduction

The mouldboard plough is a primary tillage tool and is often used to: 1) provide soil inversion that helps to bury trash, weeds and crop residue; 2) create the basis for a seedbed; and 3) loosen and aerate the soil. In Australia there is renewed interest in mouldboard ploughing to improve the potential yield of non-wetting sandy soils by burying the top layer of non-wetting soil and bringing to the surface soil that is more suitable for plant growth (GRDC, 2014). In order to improve the effectiveness of soil burial through ploughing, understanding the soil movement process is essential.

Investigations of mouldboard ploughs, in terms of soil movement, have generally relied on empirical and semi-empirical methods (e.g. Li, Lobb, Lindstrom, 2007; Van Muysen, Van Oost & Govers, 2006). Although the effect of different operating conditions, mouldboard geometries and configurations (mouldboard plough + components such as a skimmer) on soil movement can accurately be investigated

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Nomenclature

a	Indices for sphere or implement
A	Machine specific parameter
A_c	Contact area, (m^2)
b	Indices for sphere or implement
B	Machine specific parameter
C	Machine specific parameter
D	Draught force (N)
e	Coefficient of restitution
F_i	Dimensionless soil texture adjustment parameter
F_c	Cohesion force, (N)
F_n^d	Normal damping force, (N)
F_t^d	Tangential damping force, (N)
F_n	Normal total contact force, (N)
F_n^s	Normal contact force, (N)
F_t^s	Tangential contact force, (N)
F_t	Tangential total contact force, (N)
I	Moment of inertia, (kg m^2)
K_1	Stiffness for loading, (N m^{-1})
K_2	Stiffness for unloading/reloading, (N m^{-1})
M	Moment, (N m)
M_r	Moment due to rolling friction, (N m)
m	Mass, (kg)
m_{eq}	Equivalent mass, (kg)
n_c	Damping factor
n_k	Stiffness factor
R	Rotational acceleration, (rad s^{-2})
r	Radius, (m)
r_{eq}	Equivalent radius, (m)
r_{con}	Perpendicular distance of contact point from the centre of mass, (m)
S	Speed (km h^{-1})
T	Tillage depth (cm)
U_{abn}	Normal component of the relative displacement, (m)
U_{abt}	Tangential component of the relative displacement, (m)
U_0	Residual overlap, (m)
$\mathring{U}_{abn}$	Normal component of the relative velocity, (m s^{-1})
$\mathring{U}_{abt}$	Tangential component of the relative velocity, (m s^{-1})
$\ddot{U}$	Translational acceleration, (m s^{-2})
Y	Yield strength (MPa)
W	Machine width (m)

Greek letters

μ	Coefficient of friction
μ_r	Coefficient of rolling friction
λ_θ	Unit vector of angular velocity
ξ	Cohesion energy density (J m^{-3})

using experimental studies, only a small number of mouldboard geometries can be tested due to this resource intensive and costly procedure. If, however, the interaction between soil and mouldboard plough could be modelled using computational techniques, it would allow for optimisation of different mouldboard shapes and configurations without limiting the amount of geometric features and soil conditions that could be investigated.

Modelling of the soil–tool interaction is a highly complex process due to the variability of the soil structure and its non-linear behaviour. In order to simulate the soil–mouldboard plough interaction, the discrete element method (DEM), which is a dis-continuum numerical method can be used. In DEM, the bulk system is assumed to consist of distinct particles with interactions between particles applied by using contact models that are governed by physical laws. Granular soil, which is ideal for planting, comprises of distinct particles which interact only at contact points and displace independently. Hence, DEM can be used to give both force and soil movement predictions. In order to achieve realistic simulations accurate determination of pertinent DEM parameters is essential. Although there is an emerging body of knowledge in the literature regarding to the DEM modelling of soil–tool interactions (e.g. Asaf, Rubinstein, & Shmulevich, 2007; Bravo, Tijskens, Suárez, Gonzalez Cueto, & Ramon, 2014; Chen, Munkholm, & Nyord, 2013; Li & Chen, 2016; Obermayr, Vrettos, Eberhard, & Däuwel, 2014; Okayasu et al., 2012; Sadek & Chen, 2015; Shmulevich, Asaf, & Rubinstein, 2007; Tamás, Jóri, & Mouazen, 2013; Tsuji et al., 2012; Ucgul, Fielke, & Saunders, 2014a) nothing yet examines full-size soil–mouldboard plough interactions. In their research, Ucgul, Saunders, and Fielke (2017) used DEM to validate tillage forces and top soil burial for a one third scale mouldboard plough under controlled indoor laboratory conditions using a small soil bin (900 long × 500 wide × 170 mm deep).

This paper now extends the applicability of DEM to a full size mouldboard plough operating under field conditions. A field test was undertaken to measure top soil burial by a full size mouldboard plough and was then replicated using DEM. The DEM model was also used to predict top soil burial and tillage forces with respect to the effects of depth, speed, and with/without skimmer. To validate the force prediction of the DEM simulation, the ASABE's Agricultural Machinery Management Data Standard (D497.7 R2015) was used to estimate the draught requirements of a mouldboard plough for a range of operating parameters.

2. Methodology

2.1. *Field test site*

An experiment was undertaken at Nairne (35.0296° S, 138.9079° E), South Australia in September 2015 to measure top soil burial created by a mouldboard plough. The soil was a sandy loam (59% sand, 26% silt, 15% clay) with a bulk density of 1305 kg m^{-3} and 9.3% moisture content (dry basis). The field had been used for growing Brussel sprouts for the last 3 years. A location with minimal surface residue and roots in the soil was selected for the field tests.

2.2. *Experimental process*

The field tests were conducted using a three furrow commercial plough (Kverneland™ ED85) fitted with standard